Pulsars Magnetospheres

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Exploring the Non-thermal Universe with Gamma Rays

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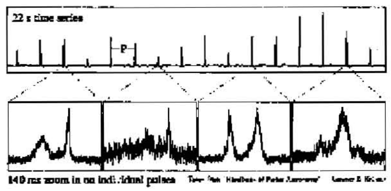
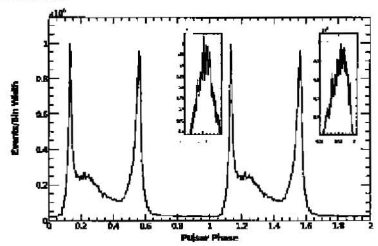
Pulsars: What we see

radio:



gamma:



- Pulse peaks are narrow

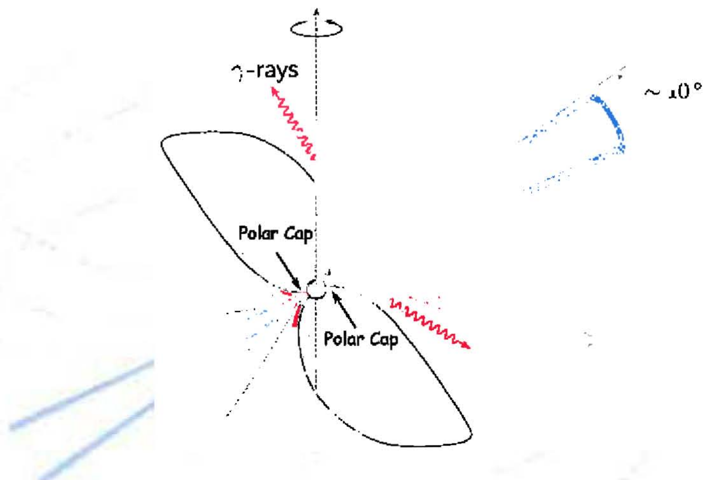
  Negligible energy budget

PWNe feed by dense plasma

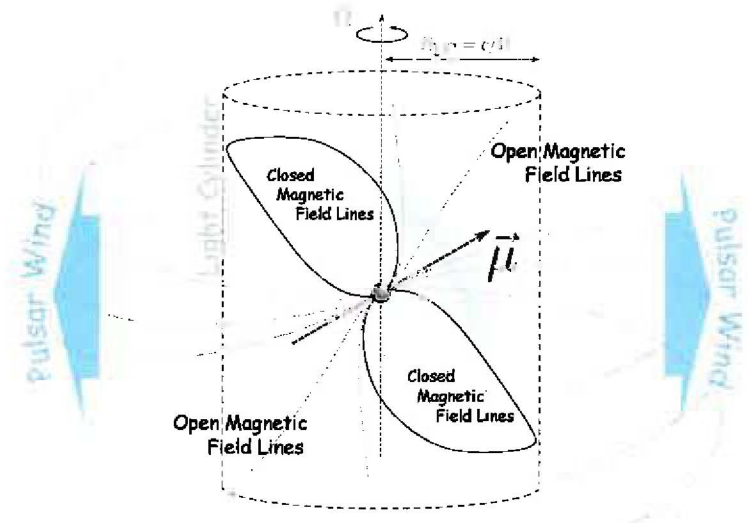
- Energy goes there

Pulsar Magnetosphere: Emission regions

"Friction" in the machine

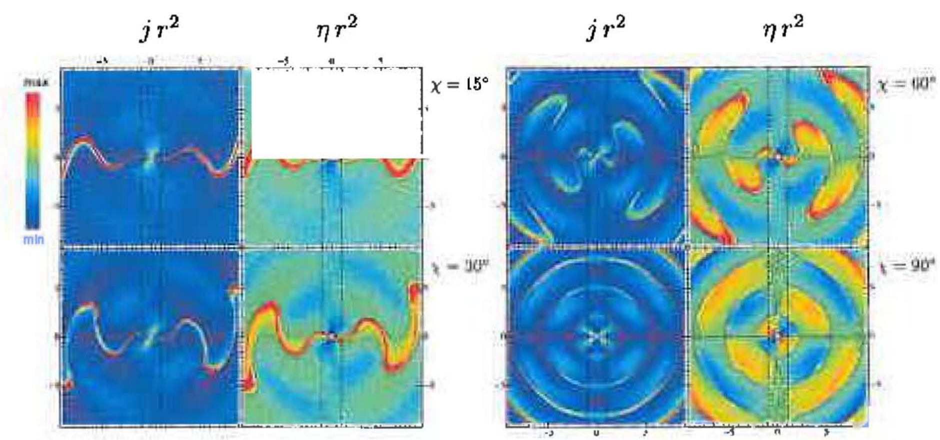


Pulsar Magnetosphere: Large scale view



Pulsar Magnetosphere: Outer parts - Wind Zone

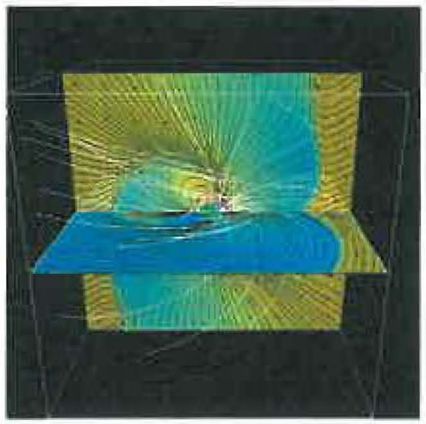
Numerical simulations of Force-Free magnetosphere

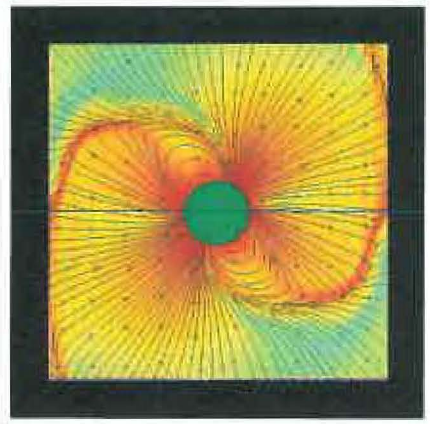


(Kalapotharakos et al. 2012)
very good match with analytical solution of Bogovalov (1999)

Pulsar Magnetosphere: Structure of inner parts

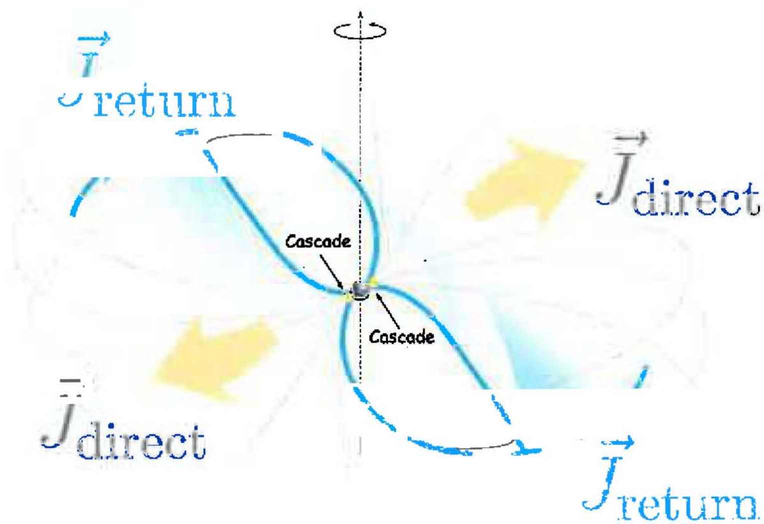
Numerical simulations of Force-Free magnetosphere





(Spitkovsky 2006)

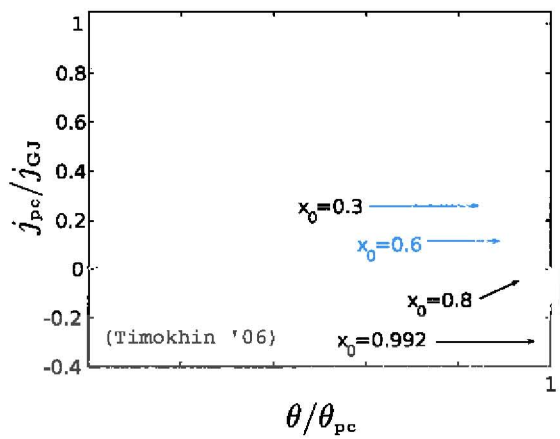
Pulsar Magnetosphere: The global circiut



Current density in the polar cap

current and charge densities are not related: $j \neq j_{GJ} \equiv \eta_{GJ} c$

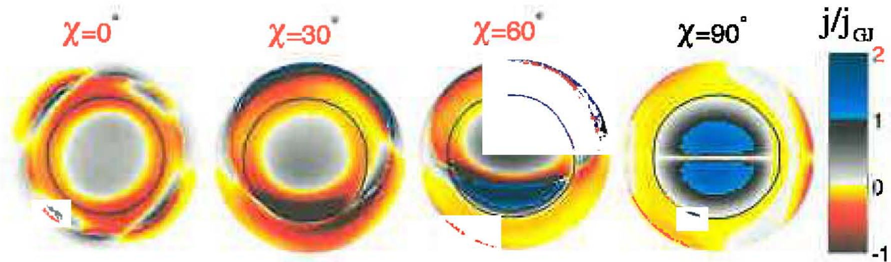
from 2D modeling of an aligned rotator



Current density in the polar cap

current and charge densities are not related: $j \neq j_{GJ} \equiv \eta_{GJ} c$

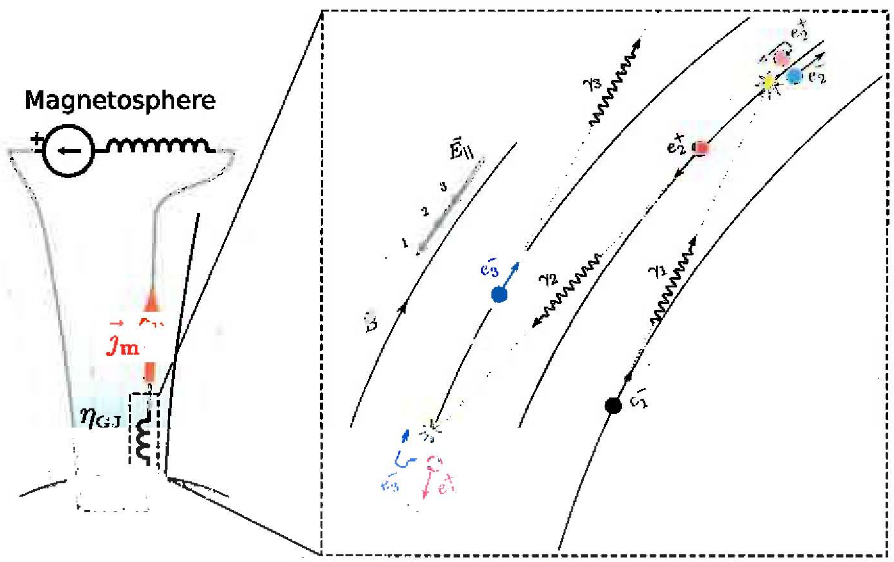
from 3D modeling of an inclined rotator



[thanks to Xue-Ning Bai (Bai & Spitkovsky 2010)]

L. Mestel, Yu. Lyubarsky, some others: "told you so!"

Physical Model: Plasma flow in an electric circuit



Boundary Conditions: Models for NS surface

- **[RS]**
  particles **cannot** leave NS surface
  ***R**uderman & **S**utherland (1975) model*

  self-consistent model: Timokhin 2009, 2010

- **[SCLF]**
  particles **freely** leave NS surface – **S**pace **C**harge **L**imited **F**low
  Arons & Scharlemann (1979) model
  (also Muslimov & Tsygan 1992, Harding & Muslimov 1998, and others)

  self-consistent model: Timokhin & Arons 2012

Numerical Model: Modeling from first principles

Numerical Code:

Particle acceleration $\leftrightarrow$ Electric field — Particle-In-Cell
Particles $\rightarrow$ Photons $\rightarrow$ Particles(Pairs) — Monte Carlo

Physical Ingredients:

- 1D Electrodynamics

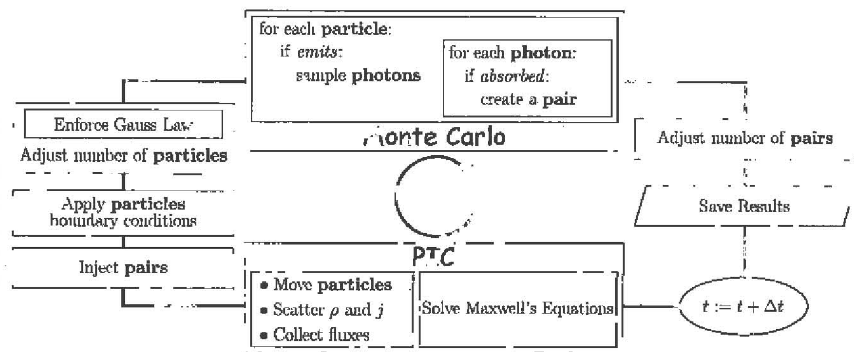
$$\frac{\partial E_{\parallel}}{\partial t} = -4\pi(j - j_m)$$

starting from

$$\frac{\partial E_{\parallel}}{\partial x} = 4\pi(\eta - \eta_{GJ})$$

- γ-ray production: curvature radiation
- pair creation: single photon absorption in magnetic field

Numerical code for cascade modeling



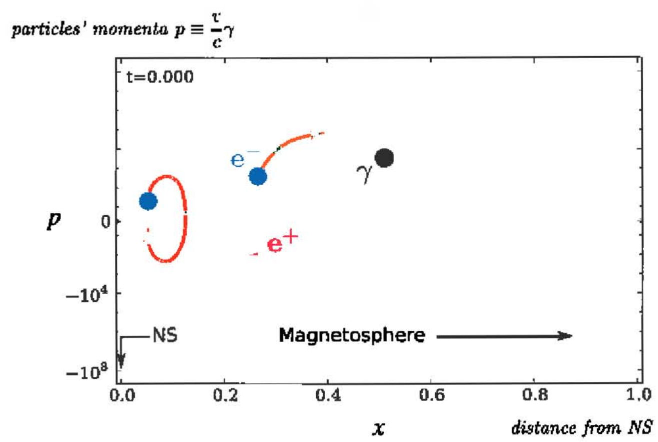
Modeling from the first principles:

Particle acceleration $\leftrightarrow$ Electric field

Particles $\rightarrow$ Photons $\rightarrow$ Particles(Pairs)

RS: No particles supplied by the NS $\quad j = j_{GJ}$

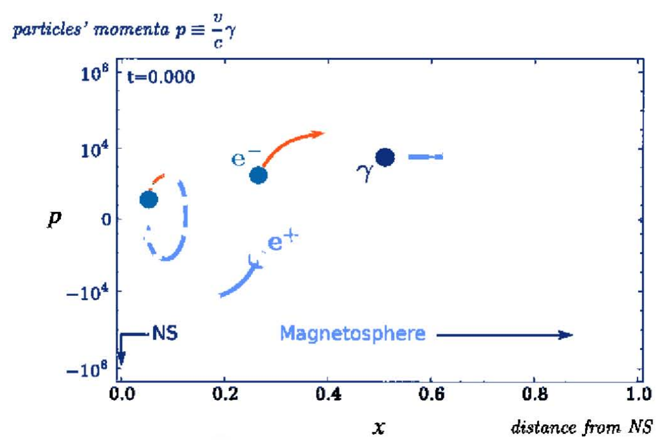
Limit cycle: series of discharges



• electrons positrons • γ-rays

RS: No particles supplied by the NS $j \quad j_{GJ}$

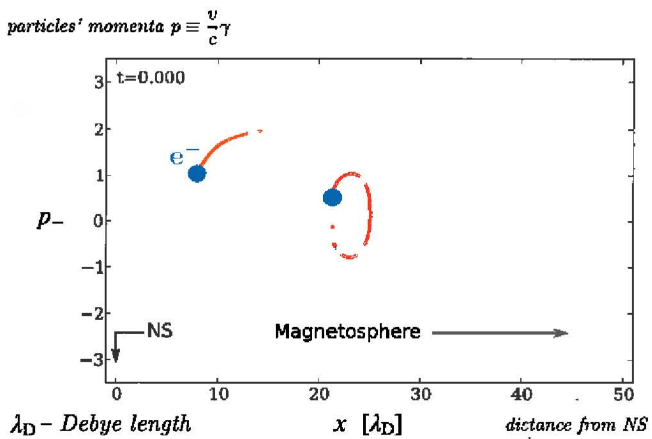
Single discharge



• electrons • positrons • γ-rays

SCLF: Low energetic flow $0 < j/j_{GJ} < 1$

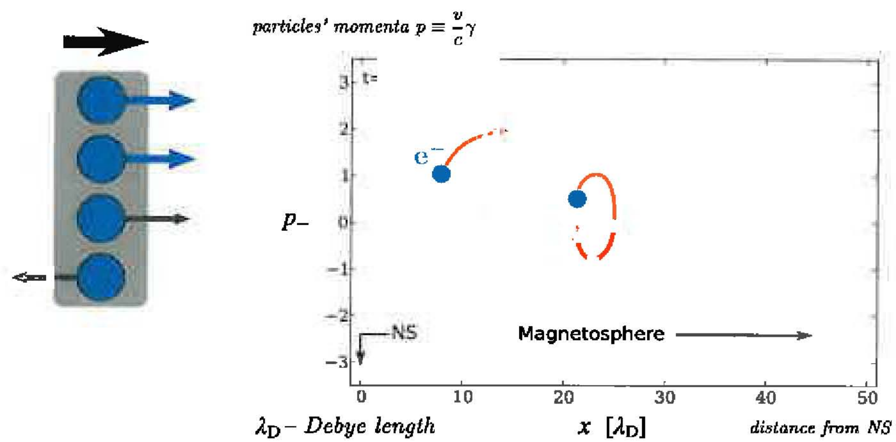
Formation of the low energetic flow



Dashed red line – oscillating solution in one-fluid approximation
Mestel & Pryce (1985), Shibata (1997), Beloborodov (2008)

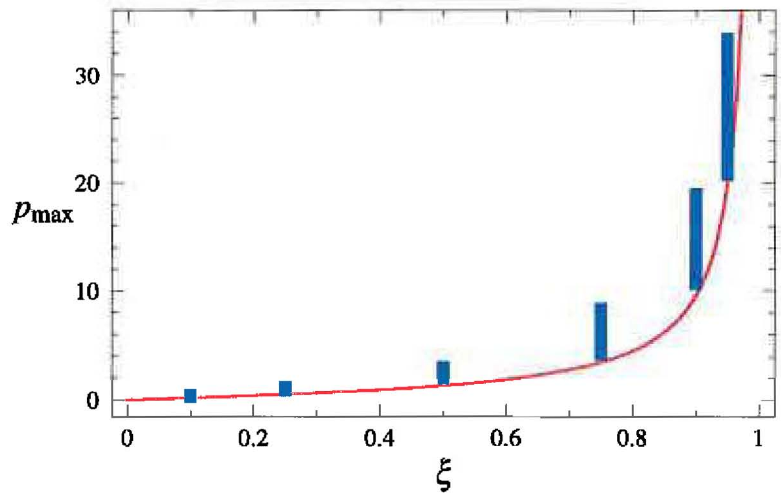
SCLF: Low energetic flow $\quad 0 < j/j_{GJ} < 1$

Current and charge density adjustment: beam and cloud

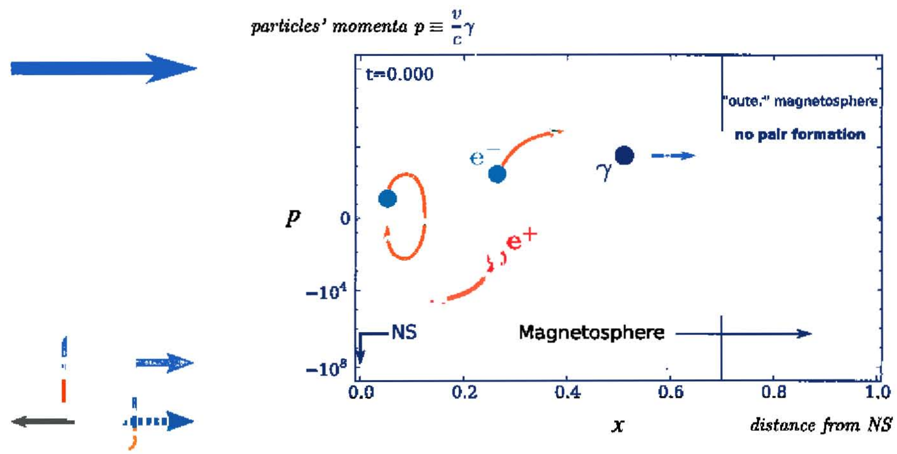


SCLF: Low energetic flow $\quad 0 < j/j_{GJ} < 1$

Maximum particle momentum as a function of $\xi \equiv j/j_{GJ}$



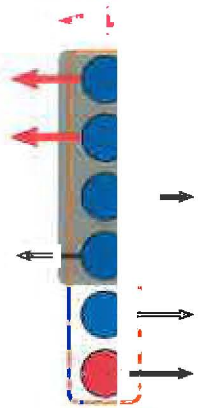
SCLF: Discharges in super-GJ flow $j/j_{GJ} > 1$

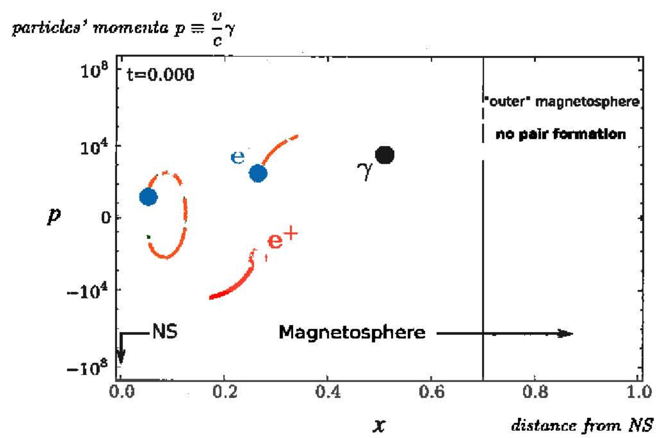


• electrons positrons • γ-rays • protons

Discharges in the return current $j/j_{GJ} < 0$

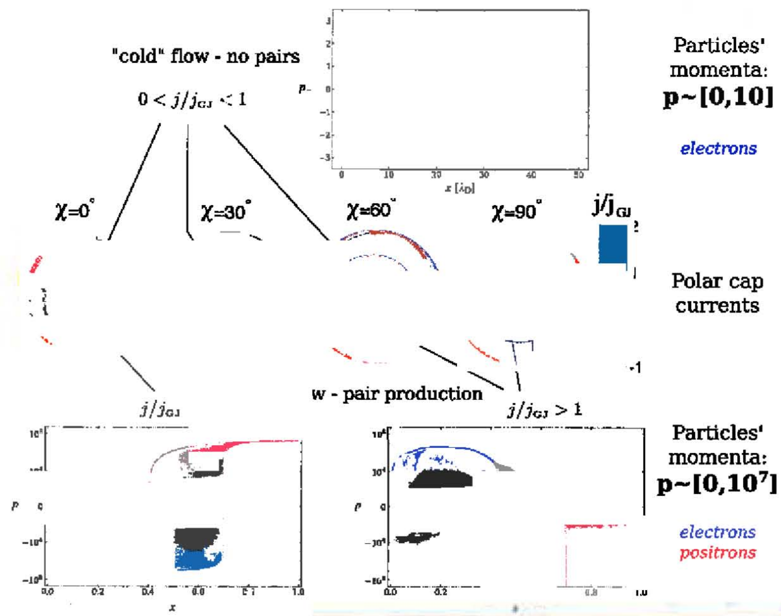
The same for both RS and SCLF



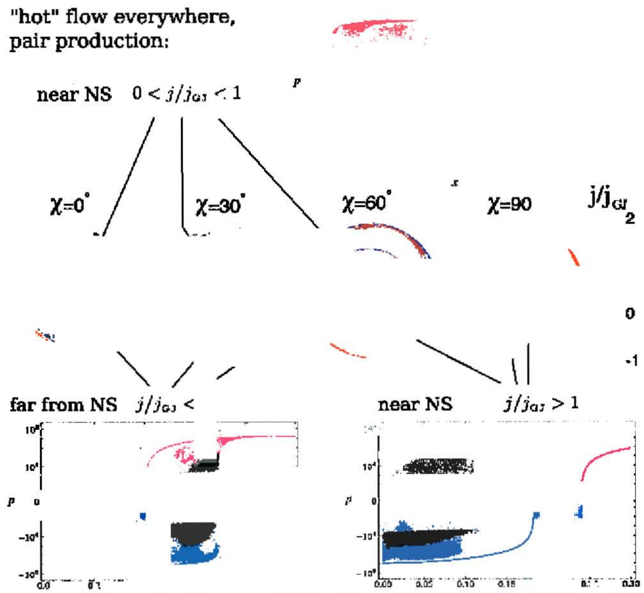


• electrons • positrons • γ-rays

Particle acceleration in SCLF regime



Particle acceleration in RS regime



Particles' momenta:
p~[0,10^7]

electrons
positrons
photons

Polar cap currents

Particles' momenta:
p~[0,10^7]

electrons
positrons
photons

Waves during discharge

It did not escape our attention. . .

RS_wave_xp_e_jp05.mp4

Conclusions

- Current density determines the plasma flow regime
- Cascades are non-stationary. ALWAYS.
- All flow regimes look different: *mutiple components (?)*
- Return current regions should have particle accelerating zones in the outer magnetosphere: γ*-ray pulsars (?)*
- Plasma oscillations in discharges: *direct radio emission (?)*

Acknowledgments

3-D model of the pulsar current sheet structure was made by

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- Constantinos Kalapotharakos (UMD/GSFC)